STRUCTURAL AND NON-STRUCTURAL BMPS FOR PROTECTING STREAMS

Richard Horner, Christopher May, Eric Livingston, David Blaha, Mateo Scoggins,
Julia Tims, and John Maxted
_ Watershed Management Institute
410 White Oak Drive; Crawfordsville, Florida 32327

ABSTRACT

Stream ecosystems in three different locations in the United States were found to benefit in a similar fashion from retention of watershed forest and wetland cover and wide, continuous riparian buffers with mature, native vegetation. The findings can help guide comprehensive watershed management and application of these non-structural practices in low-impact urban design. Intensive study of structural best management practices (BMPs) in one location found that, even with a relatively high level of attention, a minority of the developed area is served by these BMPs. Those BMPs installed are capable of mitigating an even smaller share of urban impacts, primarily because of inadequacies in design standards. Even with these shortcomings, though, results showed that structural BMPs help to sustain aquatic biological communities, especially at moderately high urbanization levels, where space limits non-structural options.

BACKGROUND

Urban Streams and Their Management

By the mid-point of the last decade the effects of watershed urbanization on streams around the United States were well documented. They include extensive changes in basin hydrologic regime, channel morphology, and physicochemical water quality associated with modified rainfall-runoff patterns and anthropogenic sources of water pollutants. The cumulative effects of these alterations produce an in-stream habitat considerably different from that in which native fauna evolved. In addition, development pressure has a negative impact on riparian forests and wetlands, which are intimately involved in stream ecosystem functioning.

What was missing at that point in time, though, was definition of the linkages tying together landscapes and aquatic habitats and their inhabitants strong enough to support management decision-making that avoids or minimizes resource losses.

Lacking this systematic picture, urban watershed and stormwater management efforts have not been broadly successful in fulfilling the federal Clean Water Act's stipulation to protect the biological integrity of the nation's waters. Effective management needs well conceived goals of what biological organisms and communities are to be sustained and at what levels, and then the foundation for judging what habitat conditions they need for sustenance and, in turn, watershed attributes consistent and inconsistent with these conditions.

Management has usually centered on attempting to reduce stormwater runoff contaminants in passive structural BMPs like ponds with permanent pools or extended detention, vegetated drainage courses, infiltration basins, sand filters, and others. Some locations also focused management attention on amelioration of peak stream flow rate increases following development to reduce erosive shear stress and its damage to stream habitats. However, there has been little tie between these prescriptions and ecological considerations, or even how well they work to sustain biological communities that they ostensibly exist to protect. What little study had been done was far too limited to draw firm conclusions, but was not promising. Maxted and Shaver (1997) were not able to distinguish a biological advantage associated with the presence versus absence of structural BMPs along Delaware streams. Jones, Via-Norton, and Morgan (1997) concluded that appropriately sited and designed BMPs provided some mitigation of stormwater impacts on Virginia stream habitats and biota, but that the resulting communities were still greatly altered from those in undeveloped reference watersheds.

Toward a More Systematic View of Watersheds, Streams, and Management

With this background of insufficient understanding of relationships among watershed and aquatic ecosystem elements, and the capabilities of prevailing management strategies to influence these relationships, the U.S. Environmental Protection Agency (USEPA) commissioned the Watershed Management Institute (WMI) to investigate stream habitats and biology across gradients of urbanization and BMP application in four regions of the nation (Austin, TX; Montgomery County, MD; Puget Sound, WA; and Vail, CO). This study followed an earlier effort along similar lines in the Puget Sound region funded by the Washington Department of Ecology. Together these studies built a database representing more than 220 reaches on low-order streams in watersheds ranging from no urbanization and relatively little human influence (the reference state, representing "best attainable" conditions) to highly urban (>60 percent total impervious area, TIA).

Results from the initial Puget Sound research and a portion of the follow-up study have been extensively reported. Biological health was assessed according to benthic index of biotic integrity (B-IBI; Fore, Karr, and Wisseman 1996) and the ratio of young-of-the-year coho salmon (a relatively stress-intolerant fish) to cutthroat trout (a more stress-tolerant species). Both biological measures declined with TIA increase without exhibiting a threshold of effect; i.e., declines accompanied even small levels of urbanization (Horner et al. 1997; May et al. 1997). However, stream reaches with relatively intact, wide riparian zones in wetland or forest cover exhibited higher B-IBI values than reaches equivalent in TIA but with less riparian buffering. Until TIA exceeded 40 percent, biological decline was more strongly associated with hydrologic fluctuation than with chemical water and sediment quality decreases. Accompanying hydrologic alteration was loss of habitat features, like large woody debris and pool cover, and deposition of fine sediments that reduce dissolved oxygen in the bed substrata, where salmonid fish deposit their eggs. The research defined stream quality zones in relation to TIA and riparian corridor condition and identified sets of necessary, although by themselves not sufficient, conditions to maintain a high level of biological functioning or prevent decline to a low level. These findings provide a basis for managing watersheds in relation to biological goals.

Follow-up Puget Sound investigation turned to the question of BMP effectiveness. This investigation considered the density of structural BMP coverage and, as ***de facto*** non-structural BMPs, extent of watershed forest cover and riparian buffering (proportion of upstream corridor with riparian zone in forest or wetland cover at least 30 meters wide on each bank). In this comparison, riparian retention exhibited greater and more flexible potential than other options to uphold biological integrity when development increases, with upland forest retention also offering valuable benefits, especially low in the urbanization gradient (Horner and May 1999). Structural BMPs at the prevailing densities demonstrated less potential than the non-structural methods assessed to forestall resource decline as urbanization starts and progresses. There was a suggestion in the data, though, that more thorough coverage would offer substantive benefits in this situation. Moreover, structural BMPs were seen to help prevent further resource deterioration in moderately and highly developed watersheds. Analysis showed that none of the options is without limitations, and widespread landscape preservation must be incorporated to retain the most biologically productive aquatic resources.

Maxted (1999) gave a preliminary report on the overall results of the WMI study available at that time. Differences in expressions of macroinvertebrate community integrity appropriate for the various locations were reconciled by scoring each relative to the best attainable measure for the region. The patterns of association between these biological expressions and TIA were similar for the Maryland, Texas, and Washington sites, and also similar to the Delaware watersheds studied earlier (Maxted and Shaver 1997), in that none exhibited a threshold level of urbanization where biological decline began. As the Delaware results had indicated, WMI stream reaches with and without structural BMPs could not be distinguished in biological quality. This preliminary analysis points out two instances of general unity among differing ecoregions in landscape-aquatic ecosystem relationships.

Additional Research Needs

Observation in the Puget Sound study area of the role played by riparian and upland forest retention in maintaining stream ecology suggests that their benefits might be found in other regions having different aquatic ecosystems. If similarity were demonstrated, the finding would not only serve the pragmatic need for targeting management attention, but would also continue to develop the picture of general unity among ecoregions. The hypothesis was tested in the Montgomery County, Austin, and Vail study areas using the data collection and analysis methods developed in the Puget Sound study. The next section of this paper presents and discusses the results.

Following up the initial Puget Sound work on the role of structural BMPs in maintaining stream health, the analysis was supplemented by more detailed evaluation of BMP service levels and added assessment of implementation quality in several catchments relatively well and poorly served with structural BMPs. A later section of this paper reports the findings.

COMPARISON OF ECOLOGICAL BENEFITS OF RIPARIAN AND FOREST RETENTION IN FOUR ECOREGIONS

Study Sites and Methods

Table 1 indicates the general levels of coverage of the four regional programs. The regional programs developed multi-metric invertebrate community indices appropriate for prevailing ecological attributes but similar in complexity. Vail watershed configurations differ substantially from the others, because of topography and other physiographic factors and the development patterns prevalent there. Most Vail area streams originate in National Forest land and flow down steep slopes to form narrow valleys containing almost all development. Overall impervious coverage in these watersheds is low relative to other study areas, although the local degree of impervious ranges up to comparable levels. In further contrast to the other regions, runoff in Vail is mostly generated by snowmelt, and relatively coarse soils are more infiltrative there. Local municipalities do not use formal structural BMPs at all and manage mainly with the non-structural strategy of riparian buffer maintenance.

Table 1. Regional Program Characteristics

Characteristic	Austin	Mont. Co.	Puget Sound	Vail[a]
Number of stream reaches	45	60	74	50
Watershed area range (km^2)	0.13-10.5	0.12-6.9	0.65-60.0	0.28-37.3
Overall TIA range (%)[b]	1.5-53.2	4.7-58.0	1.2-60.6	0-3.5
Developed range (%)[b]	0-99.7	2.6-70.2	0-96.9	0-13.9
Forest and wetland range (%)[b]	0.3-100	2.4-43.2	3.1-87.0	86.1-100
Number of metrics in invertebrate community index	9	8	9	9

[a] Range statistics are given for 25 sites with full geographic information system coverage.

[b] Overall TIA (total impervious area), developed and forest and wetland ranges are percentages of the entire watershed. Developed signifies land converted from natural or agricultural cover by construction, including lawns and other pervious covers installed by humans. For Vail, forest and wetland includes mountain meadows that are an ecological climax condition.

An Index of Riparian Integrity (IRI) was developed in a manner similar to the B-IBI formulation (Fore, Karr, and Wisseman 1996) to express with one number the key attributes of riparian zones. Scores of 1 to 4, representing poor to excellent ratings or riparian buffering, were assigned to six attributes according to the criteria in Table 2. The six scores were summed and divided by the total possible score (24) and multiplied by 100 to express the IRI as a percentage of maximum value.

Table 2. Index of Riparian Integrity Metrics and Scoring Criteria

Index of Riparian Integrity Metric	Excellent (4)	Good (3)	Fair (2)	Poor (1)
Width (lateral extent >30 m, %)	>80%	70-80%	60-70%	< 60%
Width (lateral extent >100 m, %)	>50%	40-50%	30-40%	<30%
Encroachment (% <10 m wide)	<10%	10-20%	20-30%	>30%
Corridor continuity (crossings/km)	<1	1-2	2-3	>3
Natural cover (% forest or wetland)	>90%	75-90%	50-75%	<50%
Mature native vegetation or wetland (%)[a]	>90%	75-90%	50-75%	<50%

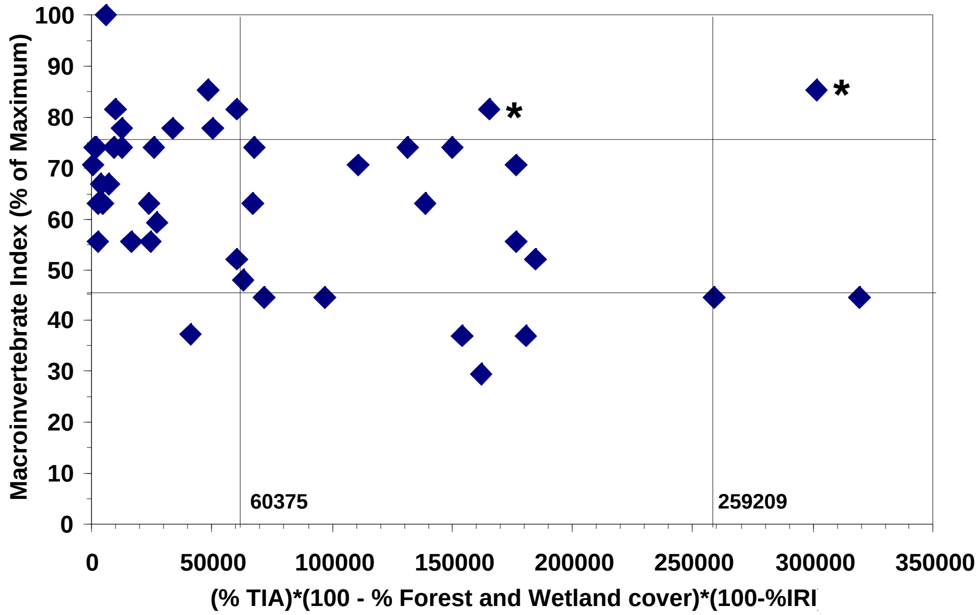
[a] "Mature" vegetation was considered to be the type, and in some cases average tree size (diameter at breast height, dbh), in the least disturbed reference sites, typical of natural riparian structure and functioning for the study location, even if not developed to the maximum extent that would be reached in more time. The definitions for each area are: Austin—ash-juniper or live oak forest; Montgomery County— >75 percent deciduous forest with dbh >23 cm (9 inches); Puget Sound— >70 percent coniferous forest with dbh >30 cm (12 inches) and native understory; Vail—patchy mosaic of aspen, spruce, fir, alder, willow, and native grasses with no clear dominant vegetation type.

The Puget Sound program quantified stream riparian characteristics during the period 1994-1997 using aerial photographs and field reconnaissance. The same exercise was performed in the other three regions with geographic information system (GIS) data that had become available by 2000-2001. These analyses involved defining bands of specified widths on both sides of stream channels and quantifying various kinds of natural and developed land cover in these bands, as well the number of anthropogenic riparian corridor breaks per unit stream length. The main product of interest from each analysis was a data set representing buffer continuity and the linear extent of riparian buffers of various widths in several vegetation cover types.

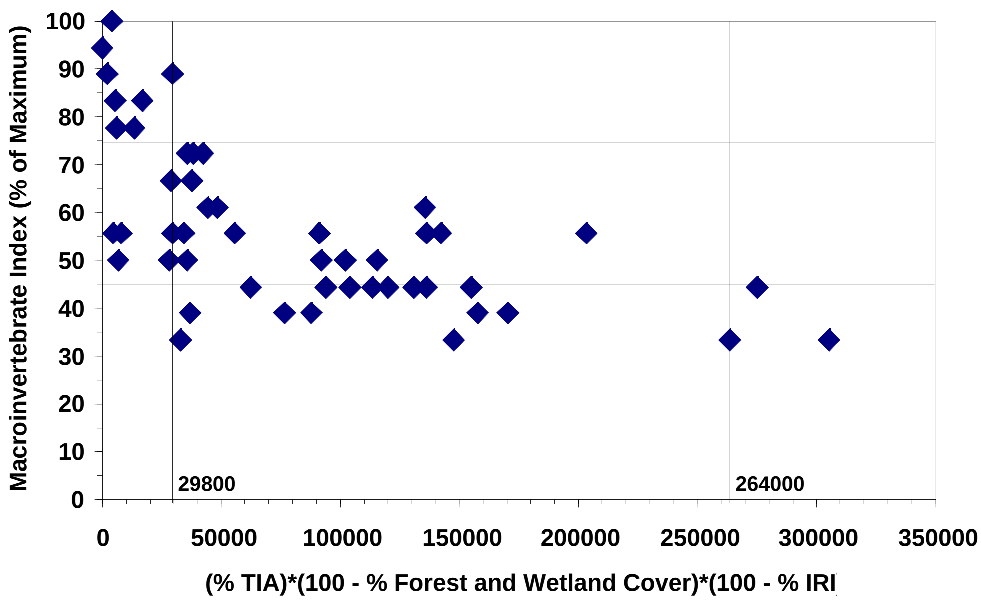
To permit comparison among study regions, invertebrate indices in each case were converted to percentage of the maximum possible score for the location. The coho salmon:cutthroat trout ratio (CS/CT) was an additional biological variable employed in Puget Sound data analysis. These dependent variables were examined relative to independent variables representing the effects of urbanization and loss of natural land cover: (1) % TIA, (2) 100-% watershed forest and wetland cover, and (3) 100-% index of riparian integrity. The independent variables were combined as products of two or all three to express multiple effects.

Results and Discussion

Figures 1a to 1d present plots of biological measures versus the combined (% TIA)*(100 - % watershed forest and wetland cover)*(100 - % IRI) variable. Analogous graphs for paired combinations of % TIA with each of the land cover variables are not shown but, for the respective geographic areas, are highly similar to those given. This similarity suggests that each area has treated its riparian zones and overall watershed forests and wetlands in much the same way.

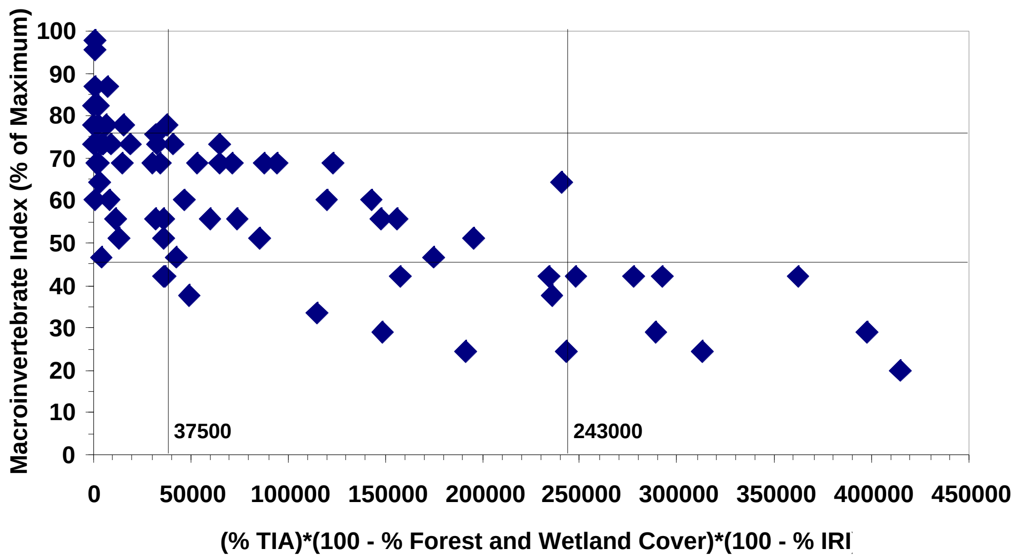


(a) Macroinvertebrate Indices for Austin

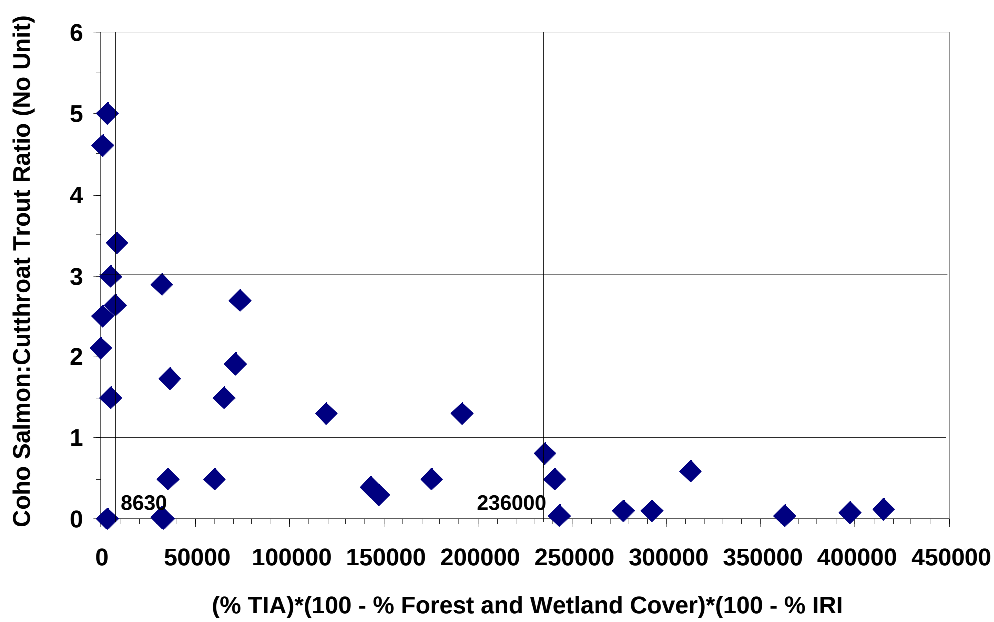


(b) Macroinvertebrate Indices for Montgomery County

Figure 1. Biological Community Indices Versus (% Total Impervious Area, TIA)*(100 - % Forest and Wetland Cover)*(100 - Index of Riparian Integrity, IRI) [Note: Left and right vertical lines indicate maximum TIA associated with high biological integrity and minimum TIA associated with low biological integrity, respectively. Numbers near the vertical lines are horizontal axis-intercepts. Austin points marked ***** are from atypically nutrient-enriched sites and were omitted from this analysis.]



(c) Macroinvertebrate Indices for Puget Sound



(d) Coho Salmon:Cutthroat Trout (CS/CT) Ratio for Puget Sound

Figure 1 Continued

Figures 1a to 1c for macroinvertebrates exhibit some quite consistent trends among regions that are discussed below. Montgomery County and Puget Sound, both humid, temperate regions with primarily perennial streams, exhibit quite similar relationships. Austin's pattern differs somewhat. It has mostly intermittent streams and, compared to Montgomery County and Puget Sound, less frequent and higher intensity rainfall and much higher evaporation. Vail data do not exhibit the general trends in Figure 1, or other clear and consistent tendencies, and are not plotted. The differences in macroinvertebrate community responses in the Vail area compared to other locations, and the lack of clear relationships with urbanization, are likely due mainly to the small proportions of large watersheds that are developed there, as well as the unique physiography and terrestrial vegetation regime of the region. Analyses were performed using local measures of the independent variables, instead of watershed-scale measures, to see if aquatic biology associates more with nearby urbanization and natural land cover than overall watershed characteristics. These local measures represent land within 100 meters upstream and on each side of the stream measured from benthic macroinvertebrate sampling sites. Local TIA ranged as high as 26.0%, still substantially under maximum watershed TIA for other study locations. These analyses were not fruitful in discerning patterns helpful to understanding functioning of Vail area streams and managing them, and further attempts will be made.

Figures 1a to 1d, along with the graphs for other combination independent variables not shown, exhibit several trends consistent among regions and ways of viewing the data:

1. The very highest biological indices in all cases are at extremely low values of the combination independent variables, meaning that in three different regions of the nation the best biological health is impossible unless human presence is very low <u>and</u> the natural vegetation and soil systems are well preserved near streams and throughout watersheds. These most productive, “last best” places can only be kept by very broadly safeguarding them through mechanisms like outright purchase, conservation easements, transfer of development rights, etc.

2. Biological responses to urbanization in combination with loss of natural cover do not indicate thresholds of watershed change that can be absorbed with little decline in health, the same as seen in the plots of biological measures versus TIA alone in earlier reports on this work (Maxted 1999).

3. Regardless of location or variables considered, relatively high levels of biological integrity cannot occur without comparatively low urbanization and intact natural cover. However, these conditions do not guarantee fairly high integrity and should be regarded as necessary but not sufficient conditions for its occurrence.

4. In contrast, comparatively high urbanization and natural cover loss make relatively poor biological health inevitable.

5. In all cases the rates of change in biology are more rapid to about the points representing crossover to relatively low integrity (the intersections of the lower horizontal and right-hand vertical lines), and then further decline becomes somewhat less rapid. This pattern is probably a reflection of communities with organisms reduced in variety but more tolerant of additional stress.

6. The points at which landscape condition takes away the opportunity for good biological health, or alternatively assures poor health, are similar among the study locations but deviate somewhat numerically. While these results might be put to general use in managing streams elsewhere, quantitative aspects should not be borrowed.

7. Comparing Puget Sound fish and macroinvertebrates, coho salmon exhibit more rapid rates of decline with landscape stress, lower TIA at which quite healthy communities can exist, and also lower TIA for poor health.

In viewing these data, a reasonable question is whether or not protecting more forest and wetland, riparian buffer, or both can confidently be expected to mitigate increased urbanization. This question has considerable significance for the ultimate success of clustering development within low-impact designs to sustain aquatic ecosystems. In beginning to think about this issue, it must first be reiterated that if the goal is to maintain an ecological system functioning at or very close to the maximum levels seen, the answer is no. If the goal is to keep some lower but still good level of health, or to prevent degradation to a poor condition, the findings suggest that there is probably some latitude.

In this case the answer to the question can be investigated by using the horizontal axis-intercepts in Figure 1 as bases for examining combinations of the landscape variables in relation to biological goals. For example, the left-hand intercept in Figure 1(d) represents the simple algebraic equation, 8630 = (% TIA)*(100 - % watershed forest and wetlands)*(100 - % IRI). That equation can be solved for any of the three landscape variables, which can then be numerically computed by substituting selected values of the other two. If, for example, the biological goal is to provide necessary conditions for a relatively healthy coho salmon population (CS/CT $\geq$3.0) with TIA = 10 percent and IRI = 65 percent, an estimate of the necessary forest and wetland retention is:

$$100 - \frac{8630}{(\%TIA) * (100 - \%IRI)} = 100 - \frac{8630}{10 * (100 - 65)} = 75\%$$

At least with the present level of understanding and confidence, analyses like this should be used in management only with caution and as advisory tools, and not as strict quantitative determinants. It must be kept in mind that, for high biological goals, the result only indicates the possibility, and not the certainty, of achieving the goal. Biological response depends on many circumstances not reflected in this simple analysis, such as where the developed area is relative to the stream and drainage pathways to it, what type of activity occurs there, and specific qualities of the natural landscape units. There are clearly limits to how much forest, wetlands, and riparian buffer can be preserved around development, particularly with the space constraints at moderate and higher urbanization levels. With all of these many factors unaccounted for, these data should be used only with care that conservatively protects resources.

If these cautions are recognized, though, watershed planners and managers can employ the findings from this multi-region study as approximate guides. The authors' hope is that their use will reduce instances of decision making without specific goals and consideration of the most crucial elements that determine their achievement. Decisions made in this way should reduce simplistic, overly optimistic approaches that very often lead to resource deterioration. Meanwhile, research should continue to represent more locations and to develop models encompassing more components of complex watershed systems.

The best and safest use of the results is probably to analyze how to prevent deterioration to lower biological integrity, or to improve health somewhat, at medium to high urbanization. For one reason, the stakes are lower in this situation, as losses have already been sustained and the relatively tolerant organisms remaining are more robust in resisting change than in more pristine areas. Also, the data show more certainty there than at lower urbanization, where favorable conditions are only necessary but not sufficient for predicting good health. Table 3 presents some cases from this part of the urbanization spectrum, computed as demonstrated in the example above. It considers only realistic forest and wetland cover and IRI values, as drawn from the regional data sets, which are quite consistent in the quantities of these variables actually present. Results for macroinvertebrates are similar between locations. For the most part, staying above what has been defined as poor aquatic health requires holding TIA under about 50 percent at usual levels of natural cover retention, or 60 percent with aggressive forest protection (about 5 percent lower in each case for Puget Sound salmon).

Table 3. Total Impervious Areas (TIA) Predicted to Be Sustainable with Specific Anti-degradation Goals and Hypothetical Natural Land Cover Cases

Location	Goal [a]	Forest and Wetland (%)	IRI (%)[a]	TIA (%)
Montgomery County	Index ≥45%	10	25	39
		20	35	51
		30[b]	40	63
Puget Sound	Index ≥45%	10	25	36
		20	35	47
		30[b]	40	58
	CS/CT ≥1.0	10	25	34
		20	35	44
		30[b]	40	55

[a] Index refers to the macroinvertebrate index for the location as percent of maximum value. Cs/CT—coho salmon:cutthroat trout ratio. IRI—index of riparian integrity.
[b] These forest and wetland cases represent an ambitious level of retention relative to the usual amount existing with fairly high urbanization.

DETAILED PUGET SOUND STRUCTURAL BMP ASSESSMENT

Introduction and Methods

Specific, direct evidence of the effectiveness of stormwater structural BMPs in protecting aquatic biota and receiving water beneficial uses is extremely sparse. As pointed out earlier, the few data do not give confidence in a clear biological payoff for the investments being made in these facilities, but are in no way adequate to warrant any solid conclusions in this regard. To add to this minimal information base, the Puget Sound component of the USEPA and WMI study conducted an intensive BMP assessment in the watersheds of four of its stream reaches, two in Big Bear Creek and one in its tributary Cottage Lake Creek (King County, WA), plus one in Little Bear Creek (Snohomish County, WA). Having received extensive management attention because of its rich salmonid fauna, the Big Bear Creek system has relatively large numbers of structural BMPs for its development level; while the Little Bear Creek reach has relatively few structural devices for the urbanization level. Sites were divided in this way because of the observation in earlier work that BMP service level (density of coverage) varied widely among the urban catchments in the study and, as seems logical, is a factor in effectiveness. These five catchments contain a total of 165 individual BMPs, about 6.5 percent of the more than 2500 found in the entire regional survey.

All BMPs were located and visited in the field, where, if above ground, their dimensions were measured and various observations were recorded. For BMPs intended to control runoff water quality (wet ponds and biofiltration swales and strips), observations included vegetation cover, erosion, and sediment deposition. Maintenance condition was noted in both quantity and quality control facilities. King and Snohomish County stormwater management agency files had information on almost all of the BMPs, which supplemented the field data collection and observations.

The assessment went beyond service level to encompass quality of implementation as well. Quantity control BMPs (mostly dry detention ponds and below-ground tanks and vaults, plus a few infiltration facilities) were rated in terms of their estimated replacement of natural soil and vegetation storage lost in development. Before development, mature, second-growth forests, almost entirely on till soils of glacial formation, covered the watersheds. For example, the Big Bear Creek site 4 catchment had >90 percent forest and wetland cover in 1985, when TIA was about 1 percent. Such conditions have been estimated to provide storage capacity for 15 to 30 cm of rainfall (Booth 1991; Booth, personal communication). Based on other local work on the till soils by Burges et al. (1989), 60 percent of this storage was estimated to be lost in the pervious portion of developed areas, and all would be lost in the impervious part. Storage replacement by infiltration devices was estimated as the volume that can be infiltrated in 24 hours as a function of the infiltration surface area provided and expected soil hydraulic conductivity. The volume detained in live storage for controlled release was taken as the replacement provided by ponds and under-ground facilities. It is recognized that, except for infiltration devices, the designs employed in these catchments are capable only of regulating peak rate discharge and not total volume ultimately released. Thus, they do not truly replace lost soil storage but only affect discharge patterns. An overall score of 100 percent for a catchment represents complete storage of all runoff from developed areas either via infiltration in 24 hours or in detention live storage.

For runoff treatment BMPs implementation quality was gauged according to recognized design and maintenance standards for maximizing performance, which were expressed as condition scores. For wet ponds the score was constructed according to wet pool volume relative to estimated design rainfall event runoff volume, ability to resist flow short-circuiting through flow path length and cellular configuration, emergent vegetation cover, and maintenance condition. For biofilters the score depended on size in relation to the estimated amount needed to provide sufficient hydraulic residence time to achieve known performance capabilities, favorable slope, energy dissipation, vegetation cover, and maintenance condition.

Scores were proportioned based on the consensus capabilities of the devices to remove two pollutants (total suspended solids and total phosphorus) and the amount of developed area served by each facility. Individual BMP scores were then added to compute an overall score for the catchment. A score of 100 percent represents interdicting all pollutants expected to be in design storm runoff from developed catchments, performance that could realistically be achieved structurally only by complete runoff infiltration.

Profile of Catchments and BMPs

Table 4 summarizes the characteristics of the catchments and BMPs given detailed attention. Watersheds are as much as two-thirds developed but largely with medium-density single-family residences, producing TIA in or near the 5 to 10 percent range. The Big Bear and Cottage Lake Creek watersheds have the greatest coverage with structural BMPs among the 38 studied in the regional project, yet only about one-sixth to one-third of the developed area even has quantity control BMPs, the primary management concentration in these salmonid streams subject to habitat destruction by more frequent elevated flows after urbanization. The average facility was built before the mid-1980s in the Cottage Lake Creek watershed, where many are below ground. Those serving Big Bear Creek average 5 years younger and tend more to be surface ponds.

The quality control service levels are even lower, especially in the older Cottage Lake Creek developments (<5 percent of developed area). The much higher numbers in the Big Bear Creek catchments indicate the turn to quality control along with quantity control in the heavy development period there around 1990. The wet pond is the most prominent BMP type, somewhat exceeding biofilters in numbers. Most wet ponds perform double service as quantity control ponds with live storage too. Many installations are wet pond-biofiltration swale treatment trains, with ponds usually but not always draining into swales. Facilities expressly designed to be infiltration devices are relatively uncommon in these glacial till catchments.

The Little Bear Creek catchment has less service of developed areas by both quantity and quality control BMPs compared to the other watersheds. These cases thus provide a contrast in management under comparable urbanization.

Analysis

Table 5 summarizes scoring of implementation quality for the two categories of BMPs. The analysis shows that <4 percent of soil and vegetation storage lost to development was recovered by BMPs in the Cottage Lake and Big Bear Creek catchments, and approximately 1 percent in the Little Bear Creek cases. These very low percentages are in strong contrast to the proportions of developed areas having quantity control BMP storage, which are about an order of magnitude greater, although still far from complete. This dichotomy signifies inadequate standards for designing these BMPs, a point discussed further below.

Achieving the full potential of water quality treatment was similarly low. The Cottage Lake Creek catchment scored near the Big Bear ones despite a much lower service level because of substantially more infiltration there, a factor also reflected in its quantity control score.

Table 4. Characteristics of Watersheds in Detailed Structural BMP Assessment

Characteristic[a]	Cott-2[b]	BiBe-1[b]	BiBe-4[b]	LiBe-2[b]
Catchment:				
Catchment area (km^2)	17.5	9.5	29.5	16.9
% developed	66.8	44.0	50.0	67.8
% impervious	11.1	6.6	8.3	9.9
Quantity Control (Qn) BMPs:				
No. Qn BMPs	56	22	59	17
% Qn BMPs below ground	41.1	9.1	32.2	11.8
% developed area with Qn BMPs	30.9	24.2	15.9	11.5
No. Qn BMPs/km^2 developed area	4.8	5.3	4.0	1.5
No. Qn BMPs/km^2 impervious area	28.8	35.1	24.1	10.2
Average age of Qn BMPs (y)	13	8	8	9
Quality Control (Ql) BMPs:				
No. Ql BMPs	11	22	49	5
No. infiltration devices	4	3	3	0
No. wet ponds	5	11	25	5
No. wet ponds that are also Qn BMPs	4	9	24	4
No. biofilters (swales, filter strips)	2	8	21	0
% developed area with Ql BMPs	4.6	15.4	13.5	3.4
No. Ql BMPs/km^2 developed area	0.9	5.3	3.3	0.4
No. Ql BMPs/km^2 impervious area	5.7	35.1	20.0	3.0
Average age of Ql BMPs (y)	11	8	7	9
Stream Biology:				
Benthic Index of Biotic Integrity	33	29	33	25
Coho Salmon:Cutthroat Trout Ratio	2.9	5.0	3.4	1.7

[a] Average ages are at time of stream ecology work; infiltration devices considered to be both quantity and quality controls.
[b] Cott-2—Cottage Lake Creek site 2; BiBe-1,4—Big Bear Creek sites 1 (upstream) and 4 (downstream); LiBe-2—Little Bear Creek site 2.

Table 5. Scoring of Quantity and Quality Control BMP Implementation

Score	Cott-2[a]	BiBe-1[a]	BiBe-4[a]	LiBe-2[a]
Quantity control score (%)[b]	2.0-3.9	1.5-3.0	1.2-2.4	0.8-1.6
Quality control score (%)	3.5	3.6	2.5	0.7

[a] See Table 4 note b.
[b] First number in range is score with assumption of maximum natural soil and vegetation storage (30 cm); second is with assumption of minimum natural soil and vegetation storage (15 cm).

This investigation started out to examine if the highest BMP service levels make a demonstrable difference in stream biological integrity. However, the mitigation potential provided by even these service levels proved to be so small that this question still cannot be conclusively answered. Biological measures are indeed lower in the relatively less served Little Bear Creek catchment, but factors other than structural BMPs could be responsible. Table 6 summarizes these potential factors for the four intensively studied catchments and two others with similar development but no structural BMPs at all. All of these streams are still producing salmon (generally, several species) and are thus resources to which strong management attention should be directed.

Table 6. Watershed and BMP Conditions and Stream Biological Integrity in Six Cases with Total Impervious Area in the Approximate Range of 5 to 10 Percent

Condition[a]	Cott-2[b]	BiBe-1[b]	BiBe-4[b]	LiBe-2[b]	GrCo-2[b]	LiSo-1[b]
Total Imperv. Area (%)	11.1	6.6	8.3	9.9	7.8	6.3
B-IBI	33	29	33	25	33	23
CS/CT						
% forest & wetlands	33.2	56.0	50.0	32.2	76.5	69.3
Index of Riparian Integrity	55.5	87.5	79.2	45.8	79.2	33.3
Quantity control score	2.0-3.9	1.5-3.0	1.2-2.4	0.8-1.6	0	0
Quality control score	4.1	5.4	4.2	0.7	0	0

[a] B-IBI—benthic index of biotic integrity; CS/CT—coho salmon:cutthroat trout ratio.
[b] See Table 4 note b; also, GrCo-2—Green Cove Creek site 2; LiSo-1—Little Soos Creek site 1.

The table does not present an entirely consistent picture. The Green Cove Creek reach equals the highest B-IBI among these sites without structural BMPs but high levels of forest, wetlands, and riparian buffer preservation. The LiBe-2 and LiSo-1 sites exhibit the lowest B-IBI values and also substantially lower riparian indices than the other locations. Still, Cott-2 equals the highest B-IBI with the highest and oldest development, nearly the least forest and wetlands, and only moderate IRI. It cannot be dismissed that this system is holding its level of health with the contribution of structural BMPs, even with their overall low service level and quality of implementation. Big Bear Creek has been the beneficiary of a King County program of fee-simple and conservation easement purchases that has encompassed 10.4 and 3.6 percent of the BiBe-1 and 4 catchments, respectively. These efforts are undoubtedly contributing to the thorough riparian buffering and moderate forest and wetlands retention seen there. Still, in biological measures these sites do not rise above the nearby Cottage Lake Creek catchment, which has very little (0.2 percent of the catchment) of these protected lands.

What is probably the safest observation is that many sources of natural variation in these ecosystems make clear-cut definition of cause and effect elusive. However, the general conclusion of the primacy of riparian buffering drawn in the preceding section appears to be upheld by these observations, and structural BMPs cannot be dismissed as contributing. Verification of that premise and delineation of how much protection they can actually afford requires their thorough and high quality implementation and then follow-up ecological study.

Discussion

The analysis determined that, even in the watersheds around Puget Sound best served by structural BMPs, a distinct minority of the development has any coverage at all. The existing BMPs mitigate very small percentages of the hydrologic and water quality changes accompanying urbanization. To understand how this situation came about, it is worth reviewing some history of stormwater management in King County, which has jurisdiction over the relatively well served watersheds.

Agency records show the first detention ponds appearing in 1975. The first King County stormwater management regulation aimed at protection of aquatic ecosystems came in 1979. From the beginning of regulation, exemptions from compliance existed for relatively small developments (e.g., no requirement unless the development would create at least 5000 ft^2 of impervious surface). Many development projects are single dwellings or small short plats fitting in the exempted category. Exemptions largely explain why much of the developed area has no structural BMPs.

The 1979 regulation specified peak rate control ponds on the basis of a hydrologic estimation procedure based on the Rational Method. This rather crude procedure produced very inadequate pond sizes relative to vegetation and soil storage losses. These inadequacies resulted from the tendency of the method to underestimate pre-development discharges, which gave an artificially low target for post-development controls. Overall, detention ponds designed in this way recovered under 10 percent of the estimated lost vegetation and soil water storage (Booth, personal communication). These ponds thus gave very little water quantity control and, without any provisions for runoff treatment, no water quality mitigation.

A new King County regulation based on an improved method for hydrologic analysis (Santa Barbara Unit Hydrograph) took effect in 1990. This regulation also introduced water quality control requirements for the first time. Peak rate control ponds designed under it can replace perhaps two or three times as much lost storage as the preceding method (Booth, personal communication), an amount that still represents a small minority of the natural storage capacity. However, applicable law vests development applications filed before adoption of a new regulation at the standard prevailing at the time of application. In the rapid urbanization climate in the area ***circa*** 1990, many applications came under the old standard well into the 1990s. As a result, the large majority of the facilities in place when the stream ecology surveys were performed (1994-1997) were based on the very inadequate 1979 design criteria. Continuing deficiencies in design standards largely explain why, even where they are present, the facilities mitigate so little of the impact. These dual regulatory inadequacies of widespread exemption and insufficient implementation standards make inevitable the small beneficial effect of structural management, even where valued resources get a relatively high level of attention.

Relationship of Structural and Non-structural BMPs

Stormwater and urban water resources management first developed around the concept of structural BMPs but recently broadened to encompass principles often given names like conservation design and low-impact development. Most fundamentally, these principles guide where to place development and how to build it to minimize negative consequences for aquatic ecosystems. There are many specific tools to implement them, but they fit generally into the broad categories of separating development from water bodies (i.e., retaining riparian buffers); limiting impervious area in favor of natural vegetation and soil, especially forest cover; and strategic and opportunistic use of structural BMPs. The Puget Sound database offers some opportunity to examine how these structural and non-structural strategies might fit together and what they can accomplish in different urbanization scenarios.

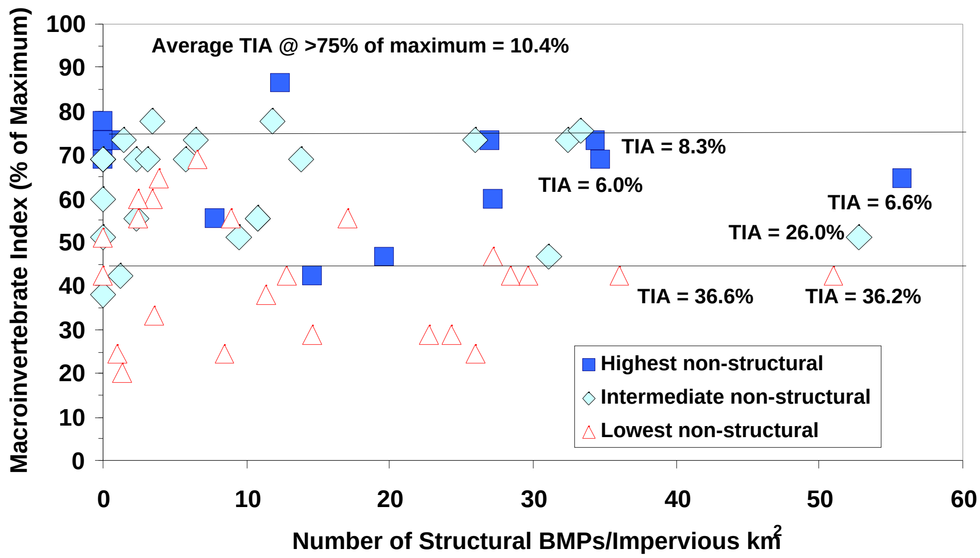
Figure 2 encompasses the various general elements of conservation design and how they relate to stream biology in terms of macroinvertebrates and fish. Structural BMPs are expressed as the density of BMP coverage per unit area of impervious surface (sites with TIA <5 percent do not have structural BMPs and are excluded). Non-structural practices are represented as the product of watershed forest and wetland cover (percent) times index of riparian integrity (percent of maximum) and graphed for the highest, intermediate, and lowest one-third of the resulting numerical values.

The first observation that should be made about Figure 2(a) is that the five highest macroinvertebrate indices are not represented, because they are from sites with <5 percent TIA. It is apparent that neither structural nor non-structural measures, at least at the levels represented in this database, can provide for the highest benthic macroinvertebrate integrity if any but the most minimal development occurs.

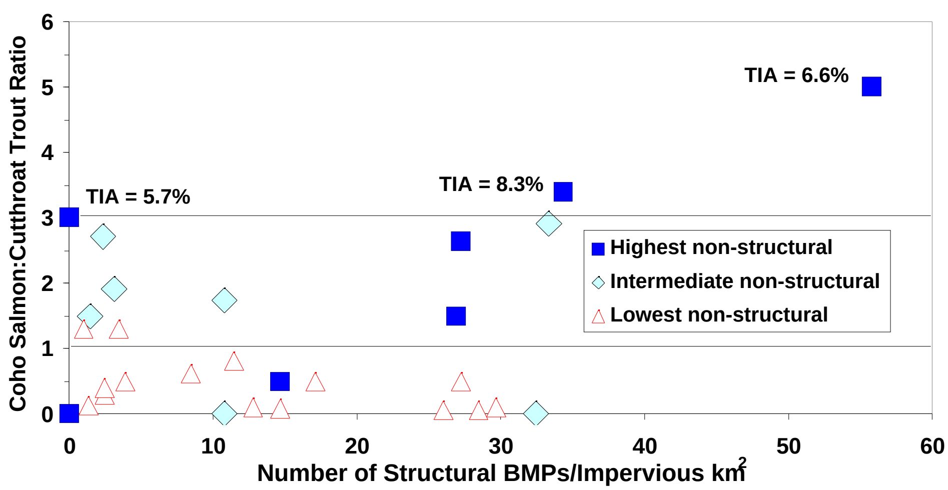
It can further be observed in Figure 2(a) that points at the left (relatively few BMPs) disperse widely over the macroinvertebrate index range. Some sites with little forest, wetland, and riparian retention rise into the intermediate biological integrity zone (45 to 75 percent of maximum index value), while a few locations with higher non-structural measures fall close to or into the region of relatively low ecological health. This observation is an expression of what is also apparent in Figures 1a to 1d, namely that a certain ecological status is not assured by any condition, or even combination of conditions, but is only more likely with those conditions.

The Figure 2(a) points converge with increasing structural BMP density, overall and in each non-structural category. Sites with the lowest macroinvertebrate indices (and also highest urbanization and lowest non-structural measures) appear to benefit from structural BMP application; while those with higher biological and natural cover measures and lower urbanization do not, with the result that points tend toward the intermediate biological level. If ecological losses are to be stemmed at high urbanization, structural BMPs appear to have a substantial role. In this situation development has taken forests and wetlands and intruded into riparian zones, reducing the ability to apply non-structural options.

Given the dearth of data, Figure 2(b) gives a scantier picture for fish, but does suggest a few points. In contrast to macroinvertebrates, only the second-ranking among the five highest CS:CT ratios was in a watershed with <5 percent TIA and is missing from the graph. In further contrast, coho salmon appear to benefit from structural BMPs in relatively light urbanization, in combination with the highest natural cover retention, although the small amount of evidence cannot conclusively support this observation. These fish, therefore, seem to have some robustness in light and mitigated human presence. On the other hand, there is no evidence that BMPs can lift the CS:CT ratio from very low levels in highly urbanized catchments low in forest, wetlands, and riparian cover, although data are inadequate to disregard this possibility.



(a) Macroinvertebrates



(b) Fish

Figure 2. Puget Sound Biological Community Indices Versus Structural BMP Density with the Highest, Intermediate, and Lowest One-Third of Natural Watershed and Riparian Cover [Note: Upper and lower horizontal lines represent indices considered to define relatively high and low levels of biological integrity, respectively.]

Any conclusions from this analysis must be tempered according to the scope of the underlying data. Probably the leading factor giving caution is that no instances exist of structural BMPs being exceptionally widely applied and designed to mitigate a large share of the known impacts of urbanization. Therefore, the fullest potential of these practices has not been examined, and it is possible that extremely thorough applications would demonstrate additional benefits not suggested in these data.

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